REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Mathematical Models for Quality of Service Driven Routing in Networks

5. FUNDING NUMBERS
DAAD19-03-1-0135

6. AUTHOR(S)
Dr Erol Gelenbe

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Central Florida, School of Computer Science
Orlando, FL 32816

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
44975.6-MA

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Very large networks with varying topologies, unreliable components, and highly time varying traffic, are not amenable to traditional techniques of analysis based on traffic engineering and simulations. Traffic flows in such networks will traverse a number of hops which cannot be determined in advance and encounter traffic conditions that are also unknown. During the flow of a particular traffic stream, the network topology may change (e.g. when wireless links are numerous) and other critical conditions (such as network security) may vary. We address the control of traffic flows in such networks with the objective of meeting the needs of the military end user. Novel results obtained in this research include distributed sensible network techniques that provide a hierarchy of provably better flow control algorithms that apply to any specific QoS metric of interest, and estimates for search times of destinations in highly unknown random environments. We prove the existence and uniqueness of solutions of the non-linear equations for the computation of QoS in the presence of sensible decision algorithms. In addition we compute the average travel time of a packet that is routed in a random environment, with and without time-outs for packet re-transmission when the packet is lost.

14. SUBJECT TERMS
Computer Communication Networks. Network Quality of Service. Mathematical Models.

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

a. A "Memorandum of Transmittal," (see attached)

b. A Filled out "DD Form 882 (Report of Inventions and Subcontracts: None)

c. "Final Progress Report," including the following information:

(1) Foreword

Very large networks with varying topologies, unreliable components, and highly time varying traffic, are not amenable to traditional techniques of analysis based on traffic engineering and simulations. Traffic flows in such networks will traverse a number of hops which cannot be determined in advance and encounter traffic conditions that are also unknown. During the flow of a particular traffic stream, the network topology may change (e.g. when wireless links are numerous) and other critical conditions (such as network security) may vary. We address the control of traffic flows in such networks with the objective of meeting the quality of service needs of the military end user.

(2) Table of Contents (if report is more than 10 pages) None

(3) List of Appendixes, Illustrations and Tables (None)

(4) Statement of the problem studied

The project has examined analytical properties of quality of service based routing in networks. Both discrete and continuous mathematical models of packet routing in networks are considered. Novel results obtained in this research include distributed sensible network control techniques that provide a hierarchy of provably better flow control algorithms that apply to any specific QoS metric of interest, and estimates for routing times from source to destinations in highly perturbed or unknown random environments. We also prove the existence and uniqueness of solutions of the non-linear equations for the computation of QoS in the presence of sensible decision algorithms. In addition we compute the average travel time of a packet that is routed in a random environment, with and without time-outs for packet re-transmission when packets are lost.

(5) Summary of the most important results

The mixed wired and wireless network topologies that are becoming the norm in military communications, including fixed and ad-hoc connections, create the need to rationally exploit dynamically variable routing as a function of network conditions. Furthermore, the applications that use such networks have stringent QoS requirements such as delay, loss or jitter, as well as requirements that reflect the need for reliability and low power utilization.

Quality of Service (QoS) has now become a central issue in networks and there is a large body of literature on the problem of estimating certain specific quality of service parameters (e.g. loss or delay) for given traffic characteristics. Typically this work consider s single or multiple buffer models (finite or infinite), or models of cascaded nodes with or without interfering traffic. There has also been much work on practical routing policies designed to achieve desired QoS objectives, as well as numerous papers on the analysis of protocols such as TCP/IP. Some authors have examined control techniques which can offer QoS guarantees to traffic of different kinds, while research on exact solutions to complex network models is still under active investigation. Our research steps away from these specific questions to take a more abstract approach. We addresses some mathematical questions related to the interaction between network routing and QoS.

Our initial work has addressed the development of an appropriate mathematical framework for the problem at hand. Thus a QoS metri q, relating to some specific data unit or a stream of data units, is a non-negative random variable that we associate with a data unit and a path v in the network. Let F(i,d) be the set of all distinct, but not necessarily disjoint, paths from node i to node d in the network. A routing policy P(i,d) for source-destination pair (i,d) is a probability distribution on the set F(i,d) that selects path v with probability p(v,F(i,d)). Let n be an intermediate node on path v, so that v=ixnyd. We say that a routing policy is incremental if p(v,F(i,d)) = p(xn,F(i,n)).p(yd,F(n,d)). Note that an incremental policy is simply equivalent to one where all decisions can be taken independently at each node. We can also consider policies which are incremental only at certain selected nodes. A QoS metric for path v is a non-negative random variable q(v), which has the sub-additive property: for v=xy, $q(v) \leq q(x)+q(y)$ (w.p.1). Note that the sub-additive covers many strictly additive metrics of interest such as packet or cell loss rates, delay, path length (number of hops), and power dissipation. Other metrics such as path reliability and available bandwidth are sub-additive. We state the following result in a loose manner.

Result 1. As a consequence of sub-additivity it follows that the QoS metric of each path in a very large graph tends w.p.1 to a deterministic value, if the length of the paths grows when the size of the graph grows and tends to infinity.

Let u be a non-decreasing measurable function and q be a QoS metric. The QoS Q(v) for data units sent on the path v using policy P(i,d) from source i to destination d along the set of paths F(i,d) will be defined as the expected value Q(v)= E[u(q(v))]. For instance if q(v) is path delay and u(x)= 1[x>T], then Q(v) is the probability that the path delay is larger than T. metric q, as a metric such that q(v) increases when the probability of directing traffic into path v increases; examples include path delay and path loss ratio. An example of an insensitive QoS metric is the number of hops along a path.

A sensible routing policy (SRP) is one that chooses a path v using a probabability distribution such that p(v) is inversely proportional to Q(v). Thus a SRP is a routing policy decides on routing based only on the QoS of each path, such that whenever the value of the QoS for any path increases then the probability of selecting that path decreases. The following result characterizes the possibility to numerically evaluate the effect of such policies. The result is significant because the QoS Q results from a non-linear equation.

Result 2 For a sensible routing policy, the expected QoS of the policy given by $Q = \Sigma_v \; Q(v).p(v,F(i,d))$ exists and is unique.

Within the class of sensible routing policies, we introduce the m-sensible routing policies (m-SRP), for $m \geq 1$, from node i to destination d based on the QoS metric q, as the probability distribution

$$p(v,F(i,d)) = (Q(v)^{-1})^m / \Sigma_w (Q(w)^{-1})^m.$$

Note that a 0-SRP is just a random choice among paths, with equal probability. The expected QoS of the policy is then $Q_m = \Sigma_v \; Q(v).(Q(v)^{-1})^m / \Sigma_w (Q(w)^{-1})^m$ and we prove the following result:

Result 3 For any QoS metric q, if q is insensitive then $Q_{m+1} < Q_m$, in other words a m+1-sensible policy is always better than a m-sensible policy.

This result provides us with the means of characterizing a hierarchy of simple and yet increasingly better sensible routing policies.

Finally we have considered the time it takes for traffic to move from some node to a destination which is distance D fom the source, in a communication system represented by a random environment. The model used represents a large and unknown network in which packets travel according to a diffusion process.

Result 4 Let b be the average incremental reduction in distance of the packet to its destination in a time interval Δt, and let c be the corresponding variance parameter for the distance reduction. Then the average time needed by the packet to reach the destination is $2D/(\mid b+ [b^2 + 2 \lambda c]^{1/2}] \mid)$, where λ is the inverse of the average time it takes for a packet to be lost or destroyed in the course of the search, or $\lambda\Delta t$ is the probability that the packet is lost in a small time interval Δt during the search, and we assume that a lost packet is then replaced by a new one at the source node.

In conclusion, in this project we have developed a probabilistic theory of network routing based on QoS.

The project has been truncated to a two year period rather than the three year period initially requested, as a result of the PI's move to an institution in the UK, and thus some of the questions we initially proposed to investigate have remained open.

We have suggested that QoS metrics of interest are sub-additive along paths. We have introduced sensitive and insensitive QoS metrics, the latter being those, such as the number of hops on a path, which are not impacted by the routing policy. We have introduced incremental routing policies which constructed routing policies by taking the product of routing probabilities at selected decisions points. We have introduced myopic policies which only examine the QoS prefixes of paths to make decisions, and incremental policies which make decisions at successive decision points.

We have also introduced sensible routing policies (SRP) which use the QoS of alternate routes to select paths with some probability. For sensible routing policies, which inevitably lead to bilateral mutual dependency between routing choices and QoS, we prove that the routing probabilities exist and are unique. We have introduced a hierarchy of SRPs, which we call m-SRPs, such that 0-SRP corresponds to random routing with equal probability and have shown that increasing m can provide better QoS.

Finally we have developed continuos diffusion approximation models in order to compute the time it takes to forward traffic from some source to a destination in the presence of packet loss and time-outs.

Many of these concepts and questions also need to be extended to multicast communications, when a set of sources need to communicate with a set of destinations, and to peer-to-peer environments when sets of nodes rely on each other for information and communication.

(6) Listing of all publications and technical reports supported under this grant or contract. Provide the list with the following breakout, and in standard format showing authors, title, journal, issue, and date.

(a) Manuscripts submitted but not published: 0

(b) Papers published in peer-reviewed journals: (2)

1. "Power-aware ad hoc cognitive packet networks", Erol Gelenbe and Ricardo Lent , Ad Hoc Networks 2 pp.205 216 (2004)
2. "Sensible decisions based on QoS", E. Gelenbe, Computational Management Science 1 (1) pp.1-14 (2004)

(c) Papers published in non-peer-reviewed journals or in conference proceedings: 2

1. "An approach to Quality of Service ", E. Gelenbe, ISCIS'04, 19th Int'l. Symposium on Computer and Information Sciences, Springer Lecture Notes in Computer Science Vol. LNCS 3280 pp.1-10 (2004)

2. "Keeping viruses under control", E. Gelenbe, ISCIS'04, 20th International Symposium on Computer and Information Sciences, Springer Lecture Notes in Computer Science, acceptec for publication (2005).

(d) Papers presented at meetings, but not published in conference proceedings: 0

(2) Demographic Data **for this Reporting Period**:

(a) Number of Manuscripts submitted during this reporting period: 10

(b) Number of Peer Reviewed Papers submitted during this reporting period: 8

(c) Number of Non-Peer Reviewed Papers submitted during this reporting period: 0

(d) Number of Presented but not Published Papers submitted during this reporting period: 0

(3) Demographic Data **for the life of this agreement**:

(a) Number of Scientists Supported by this agreement (decimals are allowed): 0.75

(b) Number of Inventions resulting from this agreement: 0

(c) Number of PhD(s) awarded as a result of this agreement: 0

(d) Number of Bachelor Degrees awarded as a result of this agreement: 0

(e) Number of Patents Submitted as a result of this agreement: 0

(f) Number of Patents Awarded as a result of this agreement: 1

(g) Number of Grad Students supported by this agreement: 0

(h) Number of FTE Grad Students supported by this agreement: 0

(i) Number of Post Doctorates supported by this agreement: 1

(j) Number of FTE Post Doctorates supported by this agreement: 0.25

(k) Number of Faculty supported by this agreement: 0.5

(l) Number of Other Staff supported by this agreement: 0

(m) Number of Undergrads supported by this agreement: 0

(n) Number of Master Degrees awarded as a result of this agreement : 0

(3) "Report of inventions" (by title only) NONE

(a) Papers published in peer-reviewed journals

(b) Papers published in non-peer-reviewed journals or in conference proceedings

(c) Papers presented at meetings, but not published in conference proceedings

(d) Manuscripts submitted, but not published

(e) Technical reports submitted to ARO

(7) List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project

(8) Report of inventions (by title only)

(9) Bibliography

(10) Appendixes

d. A "Standard Form 298 (Enclosure 1)," including the following required entries:

(1) Block 2, Report Date

(2) Block 3, Report Type and Dates Covered

(3) Block 4, Proposal Title

(4) Block 5, Contract/Grant Number

(5) Block 6, Author(s)

(6) Block 7, Performing Organization Name(s) and Address(es)

(7) Block 13, Abstract (must not exceed the 200 word limitation)

(8) Block 14, Subject Terms

(9) Block 15, Number of Pages

.3. Submission: Mail Hard Copy Reports to: Over night express to: Electronic Mail to:

U.S. Army Research Office
Reports@aro.arl.army.mil
ATTN: AMSRD-ARL-RO-OI (TR)
P.O. Box 12211
Research Triangle Park, NC, 27709-2211

U.S. Army Research Office
ATTN: AMSRD-ARL-RO-OI (TR)
4300 South Miami Blvd
Durham, NC 27703-9142

FORECAST EXPENDITURE REPORT

1. Content: The research agreements awarded by ARO are reviewed before a decision is made to provide additional funding. **ARO will send** a Forecast Expenditure Report (Enclosure 4) to the awardee 90 days prior to the exercise of incremental or optional funding.
2. Requirements: Upon receipt of this report from ARO, **complete all blanks in SECTION 2 and return**:
3. Submission: Return the completed report **within 30 days of receipt** to:

U.S. Army Research Office, ATTN: (Monitors name provided by ARO)

P.O. Box 12211

Research Triangle Park, NC 27709-2211.

PLEASE NOTE: ACTION WILL NOT BE TAKEN WITH RESPECT TO THE PROVISION OF ADDITIONAL FUNDS UNTIL THE REQUESTED INFORMATION IS RECEIVED.

(4) "Scientific progress and accomplishments" (Description should include significant theoretical or experimental advances)

Network Quality of Service (QoS) criteria of interest to the Army include conventional metrics such as throughput, delay, loss, and jitter, as well as novel criterial which are just as important such as power utilization, reliability and security. Much work has been done on the analysis of network QoS based on conventional criteria (such as loss, delay and jitter) for different traffic characteristics, on the design of node and buffer scheduling policies to achieve desired QoS, and there has also been some work on the interaction between QoS and routing.

In this project we consider abstract QoS metrics which are non-negative valued random variables related to traffic flows and network paths, while QoS is the expected value of a measurable function of the QoS metric. We develop a probabilistic theory of QoS based network routing. Our purpose is not to compute specific QoS metrics related to specific networks or specific routing algorithms, but rather to obtain properties of QoS for large networks in the presence of routing algorithms, to discover inequalities between the QoS resulting from classes of routing policies, and to obtain conditions under which QoS dependent routing policies exist and are unique. We consider sensitive and insensitive QoS metrics, the latter being those, such as the number of hops on a path, which are not impacted by the routing policy while the former are the most commonly encountered such as path delay and loss. A routing policy is then defined as a probability distribution on the set of paths from a source to a destination, or to a set of destinations in the case of multicast routing, and the QoS of a routing policy is the expected value of the QoS over the set of paths with respect to the routing probability. Routing policies of most interest to us are those which depend on the QoS so that we have determined conditions of existence and uniqueness of a QoS dependent routing policies. We have introduced incremental routing which are constructed by concatenating routing decisions by taking the product of routing probabilities at selected nodes where decisions can be taken. We have considered myopic policies which only examine the QoS of prefixes of paths in order to make a probabilistic choice about the path to be taken, and deiscuss conditions under which myopic policies may be as good as policies which act upon full knowledge. We introduce sensible routing policies (SRP) which use the QoS of alternate routes to select paths and construct a hierarchy of SRPs, which we call m-SRPs, such that 0-SRP corresponds to random routing with equal probability. We have proved sufficient conditions that guarantee that an (m+1)-SRP is better than a m-SRP when the QoS metric is sensitive or insensitive.

We prove the existence and uniqueness of solutions of the non-linear equations for the computation of QoS in the presence of sensible decision algorithms. In addition we compute the average travel time of a packet that is routed in a random environment, with and without time-outs for packet re-transmission when the packet is lost

(5) "Technology transfer" WE have had interactions both with US Army PEOSTRI and with the US Army London Office. We are now involved in discussions about the US/UK ITA with ARL.

(6) "Copies of technical reports," which have not been previously submitted to the ARO, NONE